X-ray QPOs from Black Hole Binary Systems

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Abstract.
X-ray QPOs from black hole binary systems provide specialized and extraordinary tools for black-hole astrophysics. Low-frequency QPOs (LFQPOs; 0.1-30 Hz) help us to distinguish black hole spectral states, which are now understood in terms of radiation dominance by either the accretion disk, a jet, or a compact high-energy corona. LFQPOs can be remarkably strong ($rms > 20\%$ at 2-30 keV) and coherent ($Q > 10$) in the "steep power-law" state, and this imposes first-order requirements for physical models for the compact corona that powers this state. Strong LFQPOs can also be seen in the hard state (radio-loud, steady jet), particularly when the energy spectrum shows a mixture of thermal and hard power-law components. In several sources, correlations have been found between LFQPO frequency and either the integrated thermal flux or the power-law spectral index. This provides further evidence that LFQPO oscillations are tied to the energy coupling between the disk and either the jet or the compact corona.

High-frequency QPOs (HFQPOs; 40-450 Hz) are transient and subtle (rms amplitudes near 1%), and most detections occur in the steep power-law state. Three (possibly four) sources exhibit HFQPOs that primarily represent a pair of commensurate frequencies in a 3:2 ratio, with detections that cover a wide range in luminosity. Furthermore, the three pairs of QPOs appear to represent fixed frequency systems that scale inversely with black hole mass. These results provide strong encouragement to investigate HFQPOs as some type of resonance oscillation rooted in general relativity. A successful determination of the correct oscillation mechanism would yield invaluable measurement constraints on black hole mass and spin.

INTRODUCTION

Our understanding of the astrophysical importance of quasi-periodic oscillations (QPO) in black hole binaries (BHB) continues to evolve as the *Rossi X-ray Timing Explorer* (*RXTE*) pursues frequent observations of bright new transients that appear in the X-ray sky. X-ray QPOs are complex and diverse, and yet they have far-reaching consequences. QPOs play an essential role in several key science questions: e.g., what are the physical elements that distinguish the different X-ray states of BHBs? And how can we use accretion to probe the properties of black holes using the theory of general relativity?

This brief review of BHB QPOs is organized in three sections: QPOs and X-ray states; high-frequency QPOs and general relativity (GR); and comments on the science achievements that could be gained with an advanced X-ray timing mission. The QPO sections summarize material that is considered in greater detail in the review of BHBs by McClintock & Remillard (2003) [16].

Prior to the discussions of QPO properties, a few statistical facts should be noted regarding the manner in which we gain astrophysics information for stellar size black holes in the Milky Way or the Magellanic Clouds. Our ability to locate stellar size BH in the first place and to investigate their properties via active accretion largely depends on the response to X-ray transients (see [16]). Unlike the persistent X-ray emission that characterizes the super-massive BHs in active galaxies, we only see isolated outbursts (sometimes recurrent) for 15 of 18 confirmed BHBs (i.e. with secure mass measurements) in the Galaxy/LMC and 19 of 22 BH candidates (BHCs). BHCs are selected as having X-ray spectral and timing properties that closely resemble BHBs, but the dynamical evidence of a massive compact object is lacking, usually because a large amount of dust extinction prevents the measurement of the binary motion in the optical companion.

Definitions and astrophysical applications for X-ray QPOs are summarized in the review by van der Klis (2000) [44]. The conventional view is to distinguish QPOs from "broad power peaks" that may also occur in power density spectra (PDS) using a coherence parameter, $Q = \nu/\Delta\nu \gtrsim 2$, where ν is the QPO frequency and $\Delta\nu$ is the QPO FWHM, usually determined from a fit to a Lorentzian profile. Broad power peaks are another valuable investigative tool for BHBs, particularly in the hard state (e.g. [23]; [25]; [3]; [14]), but they are beyond the scope of this paper.

X-ray QPOs in BHBs represent well-defined and yet transient Fourier signatures in sources that emit radiation in the ball-park of $10^4\ L_\odot$. They can be far stronger than any X-ray oscillation predicted by the standard accretion model, and they convey first-order requirements for physical models of non-thermal emission from BHBs. Several black holes or candidates have shown three widely separated QPOs at the same time during high-luminosity exhibitions of the "steep power-law state" (e.g. 0.1 Hz, 8 Hz, 300 Hz in the top panel of Fig. 1 below). Furthermore, there is a high degree of organization in these QPO systems, particularly in the correlations between QPO properties and X-ray spectral parameters, and this theme is explained in further detail in the Sections below.

The weight of evidence supports the conclusion that QPOs are an invaluable opportunity to advance our knowledge about compact objects and accretion physics. This assessment would contradict any claims that QPOs represent details about accretion processes that are either chaotic, incidental, or irrelevant to accretion energetics.

LFQPOS AND X-RAY STATES

Progress in Understanding X-ray States

It has been known for decades that outbursting BHBs often exhibit state transitions in which the X-ray spectra and temporal variations are seen to switch from a thermal state to a non-thermal state [39]. However, it is only recently that we have fully realized that there are two non-thermal states [16], and that one of them (the hard state) is clearly associated with the presence of a radio jet [6]. This progress has allowed us to improve the physical basis for considering BHB states: there are radiation contributions from three different elements: the accretion disk (thermal X-ray spectrum), a jet (hard X-ray power law), and a compact high-energy corona (steep X-ray power law). It can then be argued that each of the three states of active accretion represents an accretion system in which one of these elements assumes a dominant role in the production of X-ray photons.

This viewpoint motivates a conclusion that BHB astrophysics should be conducted with a two-dimensional sense of "target of opportunity", in which observers must deal with the transient nature of both BHB outbursts *and* their X-ray states. *RXTE* has pioneered this vision by encouraging state-specific investigations, even for persistent X-ray sources. These science programs are empowered by an independently rotating All-Sky Monitor (1.5-12 keV in 3 spectral channels) that efficiently reaches ∼25 mCrab (1-week timescale), supplemented with PCA scans of the galactic center region, now conducted ∼twice per week with sensitivity to a few mCrab.

McClintock and Remillard [16] proposed a revision of the definitions and labels for X-ray states to highlight the physical elements that the astrophysics community has learned to recognize in either the X-ray spectra or multi-frequency spectra of BHBs in X-ray outburst. It is argued that only a few modifications are required over the "canonical" descriptions of X-ray states [39] in order to enhance this progress and to cover a large majority of BHB observations conducted with *RXTE* and previous instruments, such as *Ginga* and *EXOSAT*.

The *steep power-law state* (SPL) is defined first by the presence of a power–law component with photon index $\Gamma > 2.4$. Secondly, either there are X–ray QPOs present (0.1–30 Hz) while the power–law contributes more than 20% of the total (unabsorbed) flux at 2–20 keV, or the power–law contribution exceeds 50% without detections of QPOs.

The *thermal dominant state* (TD) occurs when the disk–flux fraction is above 75% (2–20 keV), the PDS shows no QPOs or very weak features ($rms < 1\%$), and the power continuum is also weak: $r \lesssim 0.06$ integrated over 0.1–10 Hz.

The *hard* state is characterized by three conditions: the spectrum is dominated ($> 80\%$ at 2–20 keV) by a power–law spectrum, the spectral index is in the range $1.5 < \Gamma < 2.1$, and the integrated power continuum (0.1–10 Hz) is strong: $r > 0.1$.

It should be clear that there are gaps in parameter values between these states that should correspond with intermediate conditions that would be expected during state transitions and perhaps occur on longer timescales. It is further noted that these state definitions do not apply criteria based on X-ray luminosity. Statistical correlations between states and luminosity *do exist* for many sources, particularly the probability for higher luminosity in the TD state, compared with the hard state. However, each X-ray state has now been observed to span a range of two decades or more in X-ray luminosity. There are also widespread examples of X-ray states occurring at atypical luminosities, e.g. low-luminosity SPL states in XTE J1550-564 ([11]; [30]), and the high-luminosity hard states in XTE J1650-500 [9] and GRS 1915+105 [13].

X-ray states are briefly illustrated here to highlight their differences and to show the role that X-ray QPOs have in this science. Sample observations of the BHB GRO J1655-40 are shown in Fig. 1. The top panels show the SPL state, using the X-ray spectrum and PDS for the observation with the highest luminosity among the 81 pointings conducted with the *RXTE* PCA and HEXTE instruments [32]. The steep power-law ($\Gamma \sim 2.7$; top-left) contributes 66% of the 2–20 keV luminosity, which is 1.5×10^{38} erg s^{-1} $d = 3.2$ kpc, or 0.2 L_{Edd} for $M = 6.3$ $M_\odot$ [7]. The 2-30 keV PDS (top-right) for the same observation, exhibits QPOs at 0.1, 8, and 300 Hz. The QPOs and the strength of the power-law spectrum contrast sharply with an observation in the TD state (middle panels). In that case the spectrum matches the standard accretion disk model; the thermal component contributes

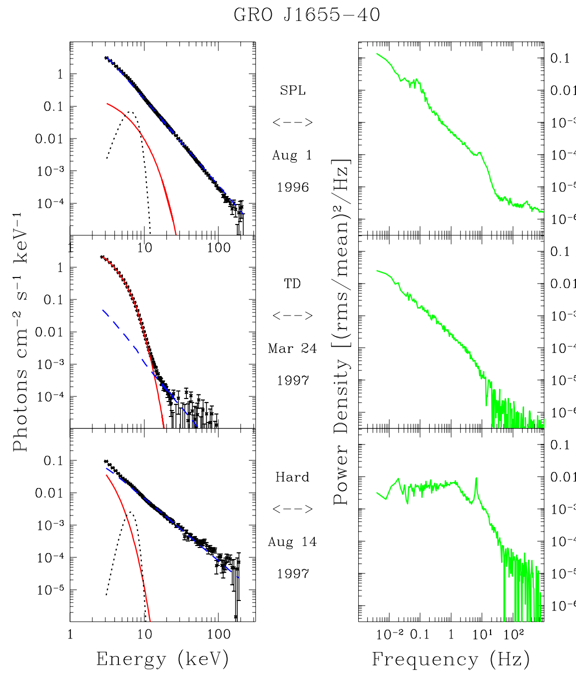

FIGURE 1. Samples of X–ray spectra and PDS for GRO J1655-40 illustrating the “steep power-law”, “thermal dominant”, and the “hard” states. The smooth lines isolate the contributions from the accretion disk (solid), the power-law continuum (dashed), and Fe $K-\alpha$ emission (dotted). Low frequency QPOs (e.g. 1-10 Hz) are very often seen in the SPL state, and occasionally in the hard state, but not in TD state.

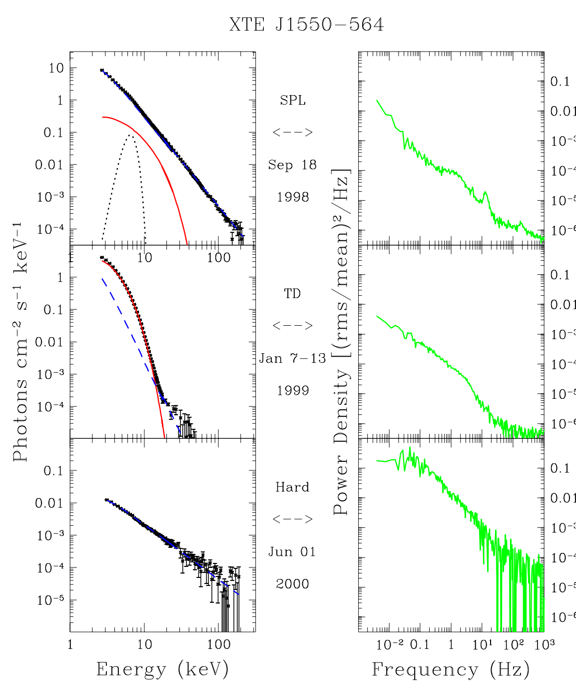

FIGURE 2. Sample spectra and PDS for XTE J1550-564 illustrating the 3 states of active accretion in black hole binaries. The data organization and line types follow the conventions used for Fig. 1.

99% of the 2-20 keV luminosity, which is near 0.1 L_{Edd}. Both the SPL and TD spectra appear "soft", when compared with the hard state. This complicates the effort to diagnose X-ray states using color-color diagrams in place of the quantitative results gained from spectral deconvolution analyses.

During the decay of the outburst, GRO J1655-40 shows a typical transition into the hard state illustrated in the bottom panels of Fig. 1. As noted above, radio astronomers have shown convincingly that the X-ray hard state in BHBs is associated with a steady type of radio jet [6]. Despite this progress, many of the detailed X-ray characteristics of the hard state are not understood. The PDS shows elevated rms variability, with a typical "band-limited" shape, which is here seen as a flat power continuum below ~ 10 Hz, falling steeply thereafter (bottom-right). In this observation, the energy spectrum shows the hard power law ($\Gamma \sim 1.7$) along with a weak disk that is comparatively cool and large (bottom left). This, along with the presence of a QPO (6.5 Hz) suggests that the transition to the hard state is not yet complete.

Fig. 2 shows very similar examples of BHB states for the case of XTE J1550-564. The SPL state is seen during the 7 Crab flare caught on 1998 September 19. Here the steep power law ($\Gamma = 2.8$) contributes 89% of the 2–20 keV luminosity, which is 1.3×10^{39} erg s^{-1} ($d = 6$ kpc), or 1.0 L_{Edd} for $M = 10\ M_{\odot}$[24]. On this occasion, QPOs are seen at 13 and 184 Hz. In contrast, the TD state (middle panels; averaged over 1999 Jan 7-13) yields a 94% thermal contribution at 2–20 keV (unabsorbed), while the luminosity is still very high ($\sim 0.6 L_{Edd}$). For the hard state, an observation is selected during the decay of the 2000 outburst (Fig. 2, bottom panels). Here the spectrum is a simple power law ($\Gamma = 1.6$; [41]), again with an elevated variability over a broad range in the PDS continuum.

LFQPO Properties and Implications

Turning back to the properties of X-ray QPOs, it is the LFQPOs that have a role in defining the SPL state. This imposes a requirement that a physical model for the compact corona must naturally produce oscillations with $rms \sim 10\%$ and $Q \sim 8.5$ on time scales of hours to days.

Even stronger LFQPOs (2-4 Hz; $rms \sim 15\%$) can be found in the high-luminosity version of the hard state displayed by GRS 1915+105 ([21]; [13]). This state is associated with a steady jet that has been resolved in VLBI radio images [5]. More common examples of the hard state at moderate luminosity (e.g. $10^{36} - 10^{37}$ erg s^{-1} from Cyg X-1 and GX339-4) do not show X-ray QPOs. On the other hand, hard state observations near times of transition, even at still lower luminosity, can show LFQPOs, as illustrated above for GRO J1655-40. If there is a common thread here, it is the propensity for QPOs in the hard state when both the disk and hard power-law components are visible in the 2-20 keV band.

Another avenue for QPO investigations is the study of phase lags and coherence functions [43] that compare two different energy bands. When the coherence is high, phase lags can be evaluated at the frequencies where LFQPOs appear. QPO phase lags have been studied for several sources, including GRS 1915+105 [21] and XTE J1550-564 ([47]; [4]; [30]). In the latter case QPO phase lags were used to define three QPO subtypes based on the value of the phase lag (i.e. positive, negative, and near zero). This might be seen as an uncomfortable complication, except for the fact that the subtypes were found to be highly correlated with the presence of HFQPOs and the particular member of the pair (with 3:2 frequency ratio) that was strong on a given occasion. The ramifications of these results remain uncertain. QPO phase lags may be caused by effects as simple as the change in QPO waveform versus energy. The fact that such subtle LFQPO details might be correlated with basic HFQPO properties illustrates both the organized behavior of QPOs and the potential diagnostic power of X-ray timing studies.

Some BHB studies have compared LFQPO measurements with spectral parameters. Correlations have been found between the QPO frequency and the integrated disk flux ([20]; [33]) and also with the power-law photon index [45]. These results imply that QPOs trace the energy coupling between the disk and power-law components. These investigations provide a framework for detailed theoretical efforts to solve the problem of the origin of the power-law spectrum.

Models for the SPL state widely invoke inverse Compton scattering as the emission mechanism [48]. However, it is very difficult to uniquely determine the geometry of the emitting region. The origin of the energetic (Comptonizing) electrons remains in doubt, although magnetic instability mechanisms have clear attractions and many proponents [18]. LFQPO models are numerous and they invoke a wide range of accretion structures and spatial scales [22]; [40]. The few models or concepts that attempt to explain both the energetics and the oscillations of the SPL state, e.g. the spiral waves in the magnetic flood scenario [38] deserve an earnest review by the high-energy astrophysics community.

HFQPOS AND GENERAL RELATIVITY

We continue to witness exciting evolution in both observational and theoretical issues related to HFQPOs in BHBs (40–450 Hz; [28]; [9]; [36]; [37]). These QPOs are

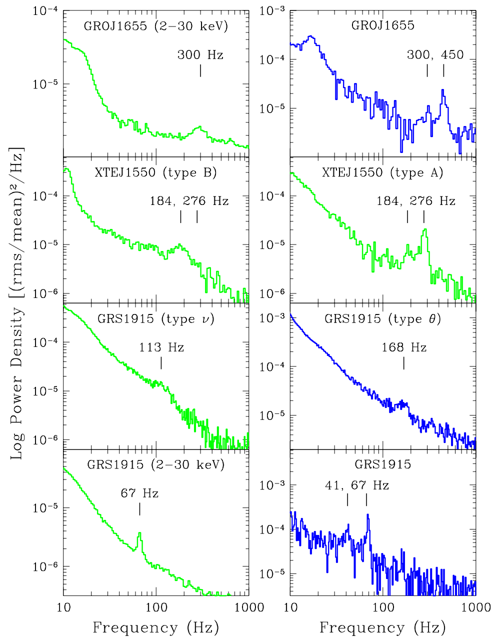

FIGURE 3. Four pairs of HFQPOs observed in three BHB systems. The first 3 rows show the HFQPOs with 3:2 frequency ratio. A gray line indicates a PDS for the range 6–30 keV, unless otherwise indicated, while a black dark line is used for PDS at 13-30 keV.

transient and subtle, with rms amplitudes that are generally ∼1–3% of the mean count rate in a given energy band. There are now 7 HFQPO detections (4 BHBs and 3 BHCs), and most of the detections occur in the SPL state. Three sources (GRO J1655-40, XTE J1550-564, and GRS 1915+105) exhibit pairs of QPOs that have commensurate frequencies in a 3:2 ratio ([28]; [29]), and there is evidence of a fourth likely case (H1732-322; [10]). GRS 1915+105 shows an additional, slower QPO pair (41 and 67 Hz) that occurs mostly in the high-luminosity observations of the TD state. The QPO pairs (excluding H1743-322) are shown in Fig. 3, while the single HFQPOs for the remaining 3 sources are displayed in Fig. 4.

These BHB QPOs are mostly derived from many *RXTE* PCA observations, and in some cases there is a substantial range in X-ray luminosity within a group [28]. The conclusion is that frequency systems are stable for a given BHB to the level of roughly 15% or less. This is an important difference from the large variations in frequency seen for both BHB LFQPOs and for the kHz QPOs in neutron-star systems.

Commensurate HFQPO frequencies can be seen as a signature of an oscillation driven by some type of resonance condition. In fact, it has been proposed by Abramowicz & Kluzniak [2] that QPOs could represent a resonance in the coordinate frequencies given by general relativity (GR) for motions around a black hole un-

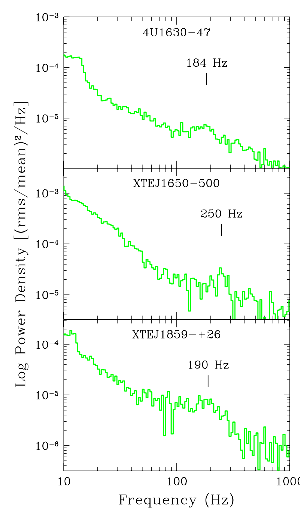

FIGURE 4. Three additional sources that exhibit a single HFQPO. The PDS energy band is 6–30 keV, and in each case the PDS is averaged over 10-20 observations in order to gain the detection.

der strong gravity (see [17]). Resonances in some form may be applicable to both BH and NS systems [1]. Ear-

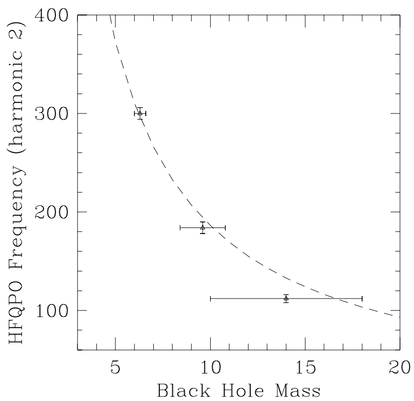

FIGURE 5. Relationship between HFQPO frequency and BH mass for the three BHBs that exhibit a pair of HFQPOs with a 3:2 frequency ratio. The frequencies are plotted for the stronger QPO seen at $2 \times \nu_0$, and the dashed line shows the best fit for a M^{-1} relation: $\nu_0 = 931 M^{-1}$.

lier work had used GR coordinate frequencies and associated beat frequencies to explain QPOs with variable frequencies in both neutron-star and BHB systems [35].

The "parametric resonance" concept hypothesizes enhanced emissivity from accreting matter at a radius where two of the three coordinate frequencies (i.e. azimuthal, radial, and polar) have commensurate values that match (either directly or via beat frequencies) the observed QPOs. For the cases with known black hole mass, the value of the dimensionless spin parameter (a_*) can be determined via the application of this resonance model if the correct pair of coordinate frequencies can be identified. In fact, reasonable values ($0.25 < a_* < 0.95$) can be derived from the observed HFQPOs for either 2:1 or 3:1 ratios in either orbital:radial or polar:radial coordinate frequencies [28].

The driving mechanism that would allow accretion blobs to grow and survive at the resonance radius has not been specified, and it is known that there are severe damping forces in the inner accretion disk [15]. On the other hand, the first MHD simulations under GR (which do not include particle interactions or non-linear perturbations) do show transient condensations in the inner disk [8]. Ray-tracing calculations under GR [31] show that the putative blobs could indeed produce the HFQPO patterns, and that the choice of $3 \times \nu_0$ versus $2 \times \nu_0$ for the stronger QPO is governed by the angular width of the accreting blob. Clearly, there is more work needed to investigate this resonance model.

A possible alternative scenario is to extend the models for "diskoseismic" oscillations to include non-linear effects that might drive some type of resonant oscillation. Diskoseismology treats the inner disk as a resonance cavity in the Kerr metric ([12]; [46]). Normal modes have been derived for linear perturbations, and the extension of this theory would be both very interesting and difficult.

For three BHB systems that show HFQPO pairs with frequencies in 3:2 ratio, we have the fortune of black hole mass estimates. In most types of GR oscillations, including the coordinate frequencies discussed above, the oscillation frequency scales with BH mass as M^{-1}, with additional dependence on spin (a_*), and sometimes on radius. In Fig. 5, the HFQPO frequencies are plotted (at the frequency of the observed $2 \times \nu_0$ feature) vs. black hole mass. The dashed line shows the best fit to a simple M^{-1} relationship: $\nu_0 = 931 M^{-1}$. These results offer strong encouragement for seeking interpretations of BH HFQPOs via GR theory. And if the HFQPOs are indeed GR oscillations, then the fit suggests that the BHs have similar values of the spin parameter.

One can examine the radiation competition between the accretion disk and the power-law components for BHBs over the course of an outburst simply by plotting the integrated fluxes from each observation. The choice of plotting symbols can then be used to denote the QPO properties at each point. This is done for GRO J1655-40 and XTE J1550-564 (2 outbursts), and GRS 1915+105 (a sample of observations with fairly steady light curves) in Figs. 6. It has been shown that the patterns in these flux diagrams are largely unaffected by the choice of integration limits (i.e. using bolometric fluxes or integration limits of 2-25 keV) [28].

These diagrams show the TD state as horizontal tracks ('x" symbols) void of QPOs and yet distributed with a substantial range in luminosity. The outburst of GRO J1655-40 and the first outburst of XTE J1550-564 (left panels) were largely radio-quiet, and so the large majority of remaining points (Δ and star symbols) reflect the SPL or intermediate states [28]. Again the range in luminosity in the SPL state is displayed, and this is particularly striking for the case of XTE J1550-564. Only a fraction of the SPL observations show HFQPOs (stars). Furthermore, both sources show a clear pattern in which the HFQPO pair member at a frequency of $2 \times \nu_0$ (solid star) is systematically seen at higher luminosity, compared with the appearance of the HFQPO at $3 \times \nu_0$ (open star).

Observations in the hard state (circle) are radio-loud (when there is radio coverage), and they follow a vertical track with little disk flux. For GRS 1915+105, all of these observations also exhibit LFQPOs. Finally, the observations GRS 1915+105 that exhibit the QPO at 67 Hz are shown with solid squares. They occur generally without LFQPOs, and their location in the flux diagram associates them with the TD state, rather than the SPL

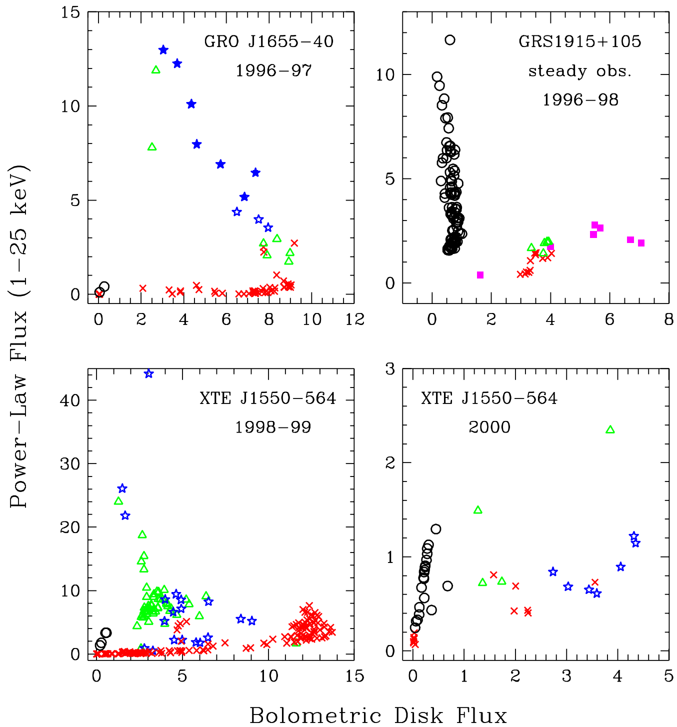

FIGURE 6. Energy division between the accretion disk and the power-law component for GRO J1655-40, XTE J1550-564 (2 outbursts) and selected, steady observations of GRS 1915+105. The symbol types denote the X-ray state and some of the QPO characteristics. Observations without QPOs are shown with an "x" symbol; all of these represent the TD state. The hard state is shown with a circle, and the SPL state is shown with a "Δ" when only LFQPOs are seen, and with a star when both LFQPOs and HFQPOs are seen. HFQPO cases are further distinguished for times when the stronger HFQPO is at $2 \times \nu_0$ (filled stars) or at $3 \times \nu_0$ (open stars). Finally, for GRS 1915+105, the times when the 67 Hz QPO is detected is shown with a filled square. The unit of flux is 10^{-8} erg cm^{-2} s^{-1} , unabsorbed.

state. There is clearly a need to construct these diagrams for all of the BHBs and BHCs observed with *RXTE* .

QPO SCIENCE WITH AN ADVANCED X-RAY TIMING MISSION

A hypothetical X-ray Timing Observatory (XTO), with capacity for a tenfold increase in effective area, compared to the *RXTE* PCA, would advance QPO investigations in two substantial and straightforward ways.

HFQPOs are a classic example of a powerful technique that is limited by 'photon-starved' observing conditions. HFQPOs are a likely window to GR applications for black holes in astrophysics. However they are subtle, transient, and currently investigated at the detection limit of *RXTE* , the only facility that can be used for this science.

For an HFQPO at 200 Hz with $rms = 1\%$ and $Q = 5$, the PCA (5 PCUs) achieves a QPO signal-to-noise (S/N) of 5σ for a 1 Crab source in 1 hour. HFQPO detections are in the regime of Poisson statistics, as there is little underlying continuum power at 200 Hz. Since the source count rate (S) is much brighter than the background rate, HFQPO detections are expected to scale as $S/N \propto S \times T^{1/2}$. An increase in collecting area is therefore the only effective way to make large advances in measurement capability.

The prospects for seeing HFQPOs at 50 σ in 1 hour are quite staggering. The search for weak harmonics can immediately be applied to the predictions for parametric resonance given by ray-tracing calculations in the Kerr metric [31]. In addition, the extreme sensitivity limits would entirely revamp our knowledge of frequency movement in HFQPOs and their strength (or upper limits) in the TD and hard X-ray states.

For LFQPOs, an XTO facility would unlock the ability to follow the individual QPO waves and track the QPOs frequency evolution. This type of investigation has been conducted with *RXTE* data [19] for a very few cases in GRS 1915+105 where slow QPOs (0.1 - 2 Hz) with very high amplitudes ($rms > 20\%$). These cases are also affected by substantial underlying power continuum, and that is a problem that requires careful analysis techniques to avoid systematic error.

The XTO would sensitively track phase shifts for LFQPOs for a wide range of sources. Investigations would also measure the evolution in the mean QPO waveform, and the variations in waveform with photon energy. This process can be conducted in the SPL state, in some hard states, and during state transitions. Such efforts would undoubtedly provide valuable information about the origin of the two forms of the X-ray power-law spectrum.

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